A System for Photon-Counting Spectrophotometry of Prompt Optical Emission from Gamma-Ray Bursts

W.T. Vestrand, K. Albright, D. Casperson, E. Fenimore, C. Ho, W. Priedhorsky, R. White, and J. Wren

Los Alamos National Laboratory, Los Alamos, NM, 87545, USA

Abstract. With the launch of HETE-2 and the coming launch of the Swift satellite, there will be many new opportunities to study the physics of the prompt optical emission with robotic ground-based telescopes. Time-resolved spectrophotometry of the rapidly varying optical emission is likely to be a rich area for discovery. We describe a program to apply state-of-the-art photon-counting imaging technology to the study of prompt optical emission from gamma-ray bursts. The Remote Ultra-Low Light Imaging (RULLI) project at Los Alamos National Laboratory has developed an imaging sensor which employs stacked microchannel plates and a crossed delay line readout with 200 picosecond photon timing to measure the time of arrival and positions for individual optical photons. RULLI detectors, when coupled with a transmission grating having 300 grooves/mm, can make photon-counting spectroscopic observations with spectral resolution that is an order of magnitude greater and temporal resolution three orders of magnitude greater than the most capable photon-counting imaging detectors that have been used for optical astronomy.

INTRODUCTION

Charged Coupled Detectors (CCDs) are currently the pre-eminent detectors for optical astronomy. Since their introduction into astronomy in the late 1970's, their dramatically higher quantum efficiency (at least a factor of 50 in the red), ease of calibration due to their highly linear response (plates have a very non-linear response), and intrinsically digital nature, have given CCDs important advantages over photographic plates. Modern CCD imagers, with spatial resolution comparable to the best photographic plates and pixel numbers approaching 10^8, have made photographic techniques obsolete. However, despite their considerable advantages as imaging detectors for optical astronomy, CCDs have an important limitation---they cannot count individual optical photons. Further, their readout time and readout noise is a limiting factor when employing short integration times to study rapid astronomical phenomena.

The ideal imaging detector for exploring the properties of rapidly varying optical emission would be an imager with photon counting capability and good spectral resolution. Here we report on a system under development at Los Alamos National Laboratory (LANL) that is designed to make photon-counting spectrophotometric observations and briefly discuss application of the technology to prompt optical emission from gamma-ray bursts.

A PHOTON-COUNTING SPECTROPHOTOMETER

The Remote Ultra-Low Light Imaging (RULLI) project is a very successful program at LANL for the development of optical photon-counting imagers. The RULLI imagers are composed of a light sensitive photocathode, a stack of three microchannel plates (MCPs), and a crossed delay line (CDL) readout, all hermetically sealed in a vacuum tube (Figure 1). When used for the detection of optical photons, they employ an S-20 photocathode, which has a quantum efficiency that allows effective detection of optical photons up to wavelengths of about 750 nanometers (Figure 2). Each photoelectron ejected by the photocathode generates a cascade in the MCP stack that produces a gain of ~10^7. The emergent electron cloud spreads over about 10 wire pairs in the tightly wound CDL grid to allow 2-D centroiding of the event to a spatial resolution of about 70 microns on the 40 mm diameter active area. This sensor tube is connected to electronics that provide absolute timing accuracy for the photon arrival times to better than 200 picoseconds. The maximum event rate for the sensor and electronics is about 10^6 events/second. This combination of spatial resolution and unprecedented ability to detect individual photons with extremely high time resolution has led to important applications in time-resolved imaging of cloud scattering and literal 3-D ranging and mapping of solid objects [1,2].

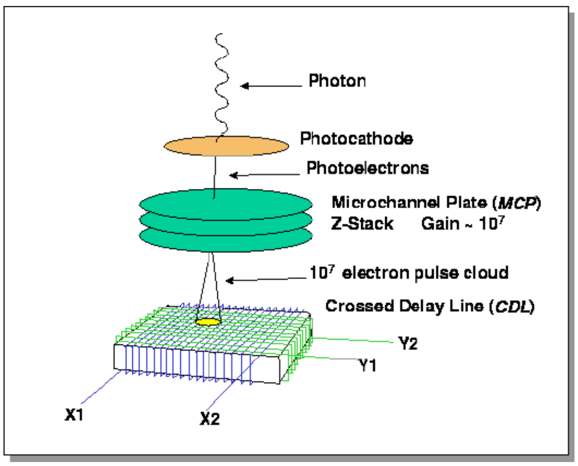

FIGURE 1. The internal components of a RULLI imager.

Application of RULLI technology has the potential to revolutionize the field of photon-counting spectrophotometry in astrophysics. A RULLI detector, when coupled with a simple transmission grating having 300 grooves per mm, can make photon-counting spectroscopic observations with spectral resolution that is an order of magnitude greater and temporal resolution three orders of magnitude greater than the best existing cryogenic detectors. The RULLI detector can also handle incident photon rates that are an order of magnitude higher, and therefore has a greater dynamic range than the cryogenic detectors. Further, since they have essentially no noise, RULLI detectors have the ability to operate at room temperature and have an observing sensitivity that is only limited by the natural sky background and the available statistics. By eliminating the power, weight, complexity, and cost issues associated with cryogenic cooling, RULLI technology is more attractive for many applications.

At LANL we are currently incorporating one of these RULLI detectors into a system designed for photon-counting spectrophotometry of rapidly varying astronomical objects. Our spectrophotometry system employs a 30-cm F7 Ritchey-Chretien telescope with a two-element field flattener that yields a spot size smaller 20 microns across the central 40mm diameter image circle. The nominal field-of-view for the telescope, when employing the full 40mm image circle, is 1.1 degrees---a size that is well matched for covering a typical HETE-2 error box. Our ruggedized telescope also incorporates Invar rods to minimize temperature induced focus variations and an interferometrically matched front window constructed of fused silica to seal the tube from dust and moisture. To obtain spectral dispersion, a transmission grating is located between the field flattener and a sensor-mounting flange that can accommodate either a conventional Apogee AP-10 CCD camera or a RULLI detector. This configuration, when used in first order with a grating of 300 grooves/mm, yields a spectral resolution of $R=\Delta E/E{\sim}700$ at 600 nm with the AP-10 CCD camera and R~110 with a RULLI detector.

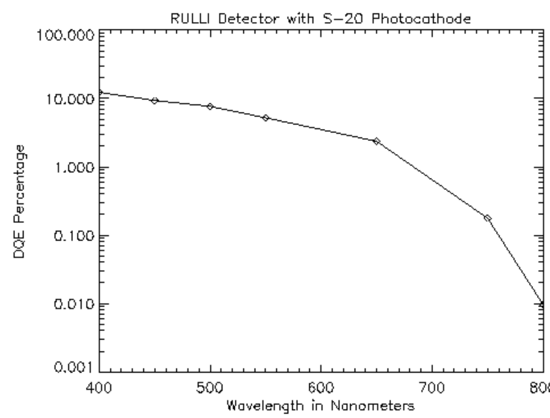

FIGURE 2. The measured Detection Quantum Efficiency (DQE) as a function of photon wavelength for a RULLI imager employing a S-20 photocathode.

To study the prompt optical emission from gamma ray bursts (GRBs), the entire spectrometry system will be mounted on a robotic rapidly slewing mount at Fenton Hill Observatory, which is located about 20 miles west of LANL in the Jemez mountains at an altitude of 8,600 feet. The rapid telescope mount, which can slew from horizon to horizon and settle in less than 3 seconds, is connected via socket to the GCN network for prompt response to GRB alerts.

SPECTROPHOTOMETRY OF GRBS

The ability of high-energy satellites to provide rapid, accurate, GRB positions in recent years led to the discovery of fading radio, optical, and X-ray afterglows at the locations of the GRBs. Optical spectroscopy of those afterglows taught us that gamma-ray bursts are more amazing than almost everyone had dared to speculate---they are the largest explosions since the big bang and contribute in a substantial way to the entire energy output of the universe. Further, for the gamma rays to escape the intense internal radiation fields requires the emitting material to be driven to Lorentz factors of 100 to 1000. Such extreme ultra-relativistic bulk flows occur nowhere else in the Universe. The extreme ultra-relativistic nature of the outflow means that the complex history of interactions and deceleration of the bulk flow, which occurs on the timescale of a day in the plasma frame, is carried by emission that arrives at Earth within the span of a minute. Unfortunately the observations of afterglows taken hours later therefore tell us little about the details of these cataclysmic events.

On January 23, 1999, a ROTSE telescope at LANL detected a short-lived luminous optical transient from the bright GRB 990123 [3]. This observation showed that prompt optical emission could also be generated during the initial GRB outburst. Most models assume that the optical emission from GRBs is synchrotron radiation generated by energetic electrons in the burst outflow. By noting that the optical and gamma ray intensities were not correlated, many authors argued that the emission in the two bands originated in different regions and suggested that the prompt optical outburst is generated as a reverse shock that traverses the relativistic outflow. Such a reverse shock can only occur once in a given GRB, and indeed, the ROTSE data seem to show a single peak leading to power-law decay. On the other hand, there are models that predict rapid optical variations were present that should be correlated with the gamma ray fluctuations that were as short as tens of milliseconds in this event [4]. The ROTSE light curve during the burst proper is composed of only three points (Figure 3), and is too highly under-sampled to definitively distinguish between models. More bursts, measured with far better temporal resolution, are needed.

Application of our photon-counting RULLI technology to this problem would have a major scientific impact. It would allow time-resolved optical spectroscopy of the evolving prompt emission and would represent an opportunity to measure the unique physics of the ultra-relativistic flow. During the rapid deceleration that occurs within the first minute or so of the gamma-ray burst, there are major parameters that define the physics of the flow: the Lorentz factor, the ambient density, the fraction of the energy in mass of the particles, and the fraction of the energy in the magnetic field. By measuring the spectral shape of the emission and how it evolves with our RULLI-based spectrophotometer, each of these parameters can be determined [5]. Thus, with our detailed photon-counting spectroscopy, we will determine the physical conditions of the only known place in the universe to have ultra-relativistic motion since the Big Bang.

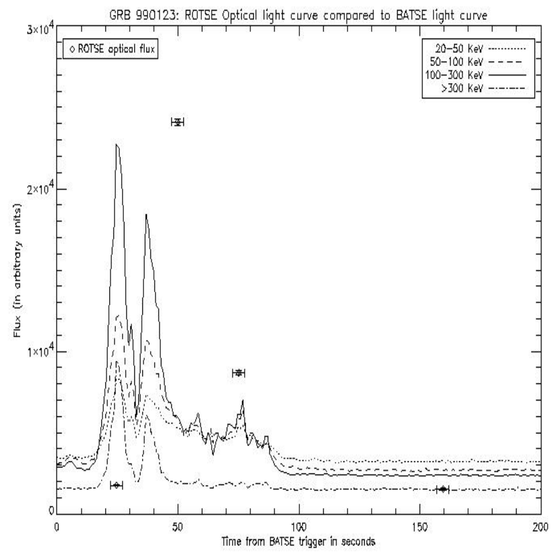

FIGURE 3. The gamma ray and optical lightcurves for prompt emission from GRB 990123. The optical lightcurve during this prompt phase is composed of only three broadband CCD measurements. RULLI will give us time-resolved spectral measurements comparable to those in the gamma rays and provide powerful tests of GRB models.

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